# Exploring New and Conventional Starting Methods of Large Medium Voltage Induction Motors on Limited kVA Sources

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**Abstract— Liquefied Natural Gas peak shaving facilities utilize large horsepower motors to drive refrigeration compressors needed for the liquefaction process. Utilities impose strict voltage flicker requirements making evaluation of various motor starting methods imperative. The large motor starting studies must be evaluated while also factoring in equipment and controls complexity and overall project capital costs. This case study will evaluate several motor starting methods, comparing technical performance and cost considerations, identifying the best method for the project requirements and reviewing the field measurements during operation confirming acceptable performance of the installed method.**

**Index Terms— Motor starting study, large horsepower induction machines, reduced voltage starters, autotransformer, full voltage, variable frequency drive, starting duty variable frequency drive, synchronous transfer**

## I. Introduction

Understanding the impact to utility voltage while starting large horsepower induction machines is critical to the reliability and continued operation of any industrial facility. There are many commonly applied motor starting methods commercially available such as: full voltage, reduced voltage, and variable frequency drive (VFD). New methods include starting duty rated VFD and synchronous transfer. Each method has its benefits and drawbacks and must be carefully considered by identifying those which meet the utility requirements while factoring in controls complexity, equipment type and project capital cost considerations, and at the same time considering the torque and acceleration requirements of the critical motor load. This case study of an actual 4175 hp compressor will evaluate all of these metrics and identify the best motor starting method given the project constraints.

## II. System description

Liquefied Natural Gas (LNG) peak shaving facilities located strategically along pipelines are a critical part of the United States natural gas distribution infrastructure. During periods when the pipeline has abundant supply of natural gas (typically the spring/summer months), the facility draws natural gas from the distribution system and, through a process of refrigeration, converts it from vapor to liquid state thus reducing its volume about 618 times. The now liquefied product is stored at its cryogenic temperature of approximately -260 F in insulated tanks. This process is referred to as Liquefaction.

Conversely, during periods of "peak" natural gas demand (typically the winter months when heating needs draw heavily on the available pipeline supply), the facility returns the liquefied natural gas stored in its tank(s) to the vapor state and reinjects the product into the pipeline helping to maintain the distribution's flow and pressure requirements. This process is referred to as Vaporization.

The Liquefaction process is fairly energy intensive with the majority of power demand consumed by the refrigeration compressor. As a result, electrically driven refrigeration compressors are traditionally served by very large horsepower motors with consequently high full load rated currents and, most importantly, high inrush starting currents (or locked rotor currents). As LNG peak shaving facilities are located along the pipeline, often the utility interconnection may be radial long overhead lines at sparse areas of the distribution system resulting in limited kVA sources, i.e. weak sources. Typical utility distribution voltages may range from 4160V to 23,000V and LNG compressor sizes may range from 2,500 hp to 7,000 hp. Depending on available utility short circuit kVA from the power grid serving the facility, this may limit choices of motor starting methods that maintain voltage drop within criteria and the most cost-effective motor starting solution needs to be assessed and selected.

### A. *Compressor operation*

The Liquefaction process operates very much like a typical

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air conditioning system where the medium to be refrigerated (i.e. natural gas) is circulated through a heat exchanger where it transfers its heat to the refrigerant medium (i.e. a mix of selected gases) and becomes progressively colder in the process.

After absorbing heat in the exchanger, the refrigerant is then compressed to a liquid state in the refrigerant compressor. The now liquid refrigerant is circulated back to the heat exchanger where pressure is suddenly dropped allowing the refrigerant to rapidly expand and return to the gas state.

This fast change of physical state from liquid to vapor ("flashing") causes the refrigerant temperature to drop significantly making it ready to remove additional heat from the treated medium and the process is repeated.

The treated medium and the refrigerant medium are kept in separate loops and the refrigerant compressor only applies compression energy to the refrigerant. The magnitude of compression energy is dictated by the target production rates but it is generally quite high requiring significant electrical energy to be drawn from the plant's electrical distribution system.

In an attempt to mitigate the electrical load demand during the starting transient of these large electrical motors, refrigerant compressors are typically equipped with process bypass piping that allows starting the compressor in an "unloaded" state, significantly reducing the torque required during acceleration, and resulting in faster acceleration times. Nevertheless, by their sheer size, these machines still impose a great demand on the power source. Therefore, careful selection of the most effective and economical motor starting method is required amongst the ones evaluated in Section III, which are: Full voltage across-the-line starting, capacitor assist starting, reduced voltage autotransformer starting (RVAT), reduced voltage solid state starting (RVSS), and variable frequency drive (VFD) starting. The new approach to VFD starting explored in this paper is partial rated VFD with synchronous transfer bypass.

### *B. LNG Peak Shaving Facility Electrical Distribution*

The LNG peak shaving facility electrical distribution system of interest is supplied by one 12,470V utility service with an available three-phase fault capacity of approximately 100MVA as shown in Fig. 1. From the service entrance or point of common coupling (PCC), a 7.5MVA transformer with 6.5% impedance is supplied by approximately 1200 feet of 2-4/0 Cu Conductors per phase. The 7.5MVA transformer steps the 12,470V service voltage down to 4,160V and supplies the motor control center via 2-500MCM/phase Cu conductors of approximately 100 feet. The motor control center supplies a 4157hp compressor motor.

In addition to utility power, this LNG peak shaving facility also has 2.5MW of solar panel arrays that feed directly onto the same utility point of common coupling.

### *C. Utility voltage drop criteria and motor accelerating time criteria*

The utility requires that the motor start does not suppress the utility voltage at the PCC more than 9% from nominal; the utility also requires that the running load does not suppress the utility voltage more than 3% from nominal at the PCC. In addition to the utility voltage requirements, the operation requires that the compressor must be brought up to speed within 25 seconds.

Although the solar field is a source of power, due to the complexity and widely varying output, however, its effect on supporting the line voltage during compressor starting was not considered. In addition, the grid tie inverters would not be able to support more than a 12% voltage drop without shutting off and remaining off line for a minimum of 10 minutes. As a result, the solar field was not considered a source of voltage support during compressor starting. Instead, the evaluation looked at minimizing the voltage drop at the solar field to minimize interaction of the grid tie controller. The solar field is a good example of commonly encountered problems of an adjacent critical load.

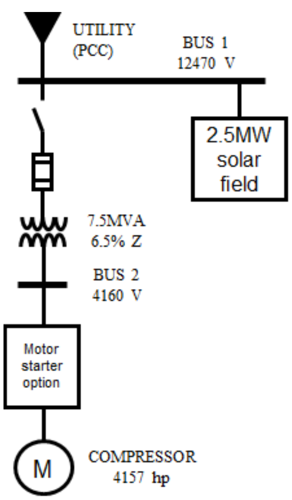


Fig. 1. Simplified one-line diagram LNG Peak Shaving Facility

The simplified one-line diagram shown in Fig. 1 depicts the utility feed, primary switch and distribution transformer. The box with the motor starter indicates the various motor starting types investigated in this paper.

### *D. Motor and compressor data*

The compressor in this application is driven by a 4160V, 4157hp, 4-pole induction motor. The motor data and performance curves are shown in Tables 1 and 2 and in Fig. 2 respectively. Notable in the performance curve of Fig. 2 is a low starting torque of 70% and a break away load torque of 10%. Because torque is proportional to voltage squared [1], the voltage drop on starting will impact the starting torque and the ability to overcome break away torque. Additionally, the motor is started with partial suction, so that load torque curve applies and will result in longer acceleration time. Both of these factors were accounted for in the motor starting simulations.

TABLE I
Compressor 4175hp Motor nameplate data

| | |
|---|---|
| Voltage | 4160 V |
| Power | 3100 kW (4157hp) |
| Full load amperes | 490 A |
| Locked rotor amperes | 3025 A |
| Rated speed | 375 rad/sec (3581 rpm) |
| Frequency | 60 Hz |
| Full load torque | 8266 Nm (6097 lb-ft) |
| Locked rotor torque | 5785 Nm (4267 lb-ft) |
| Breakdown torque | 17523 Nm (12925 lb-ft) |
| Combined WK2 | 65.5 kg-m2 (1556 lb-ft2) |

TABLE II
Compressor 4175hp Motor nameplate data, continued

| Load | 0% | 25% | 50% | 75% | 100% | Locked Rotor |
|---|---|---|---|---|---|---|
| Efficiency | N/A | 94.2% | 96.1% | 96.5 | 96.3 | N/A |
| Power factor | 0.069 | 0.773 | 0.888 | 0.911 | 0.913 | 0.132 |
| Amperes | 83.1 | 147.8 | 252.2 | 367.2 | 489.5 | 3025 |

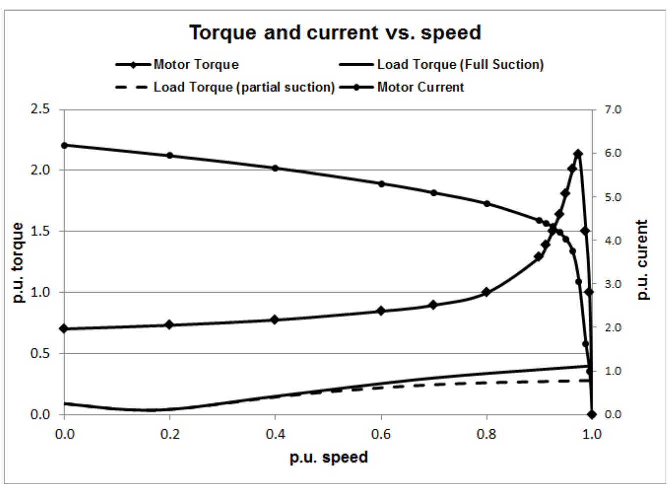

Fig. 2. Compressor 4175hp Motor Performance Curves

## III. Simulation and Analysis of Starting Methods

Transient motor starting analysis was performed to evaluate the various methods of starting the compressor and the impact on the utility PCC. A model of the electrical distribution system from the utility PCC to the 4175hp motor was developed in the transient motor starting program. The induction motor model included the motor electrical torque and current characteristics, load torque model of partial suction, and inertial effects of the motor and compressor load. Five starting methods of starting the 4175hp compressor were simulated and analyzed: (A) Full voltage or across-the-line starting, (B) capacitor assist starting, (C) reduced voltage autotransformer starting (RVAT), (D) reduced voltage solid state starting (RVSS), and (E) variable frequency drive (VFD) starting. Each starting method was evaluated with the compressor lightly loaded (partial suction). The same system and motor electrical parameters were used for each study case, changing only the starter type. Voltage, current, motor speed, acceleration torque, and acceleration time were calculated for each case. Selected results are shown in subsequent sections.

### *A. Line Start*

Full voltage motor starting or across the line starting is the most basic and cost-effective method of motor starting. Most motor starters are comprised of a disconnect, power fuses, and a contactor. Typical contactor construction uses vacuum bottles but older starters utilized air or oil as the interrupt medium. The contactor is an integral part of all motor starters, helping to ensure reliable operation, starting and stopping the motor as needed. Fig. 3 illustrates an electrical one-line diagram and photo of a typical starter.

Across the line motor starting requires fuse and contactor coordination to ensure the fuses do not prematurely fatigue or open during high motor inrush currents. Conversely, the fuses are sized in order to interrupt high-level fault currents that the contactor cannot. The inrush (or locked rotor) currents typically range from 5 to 10 times full load amperes depending upon the construction and NEMA type [2]. The inrush current can last until the motor and driven load has reached rated speed. This duration is called the motor starting time and typically should be less than the maximum allowable locked rotor time of the motor.

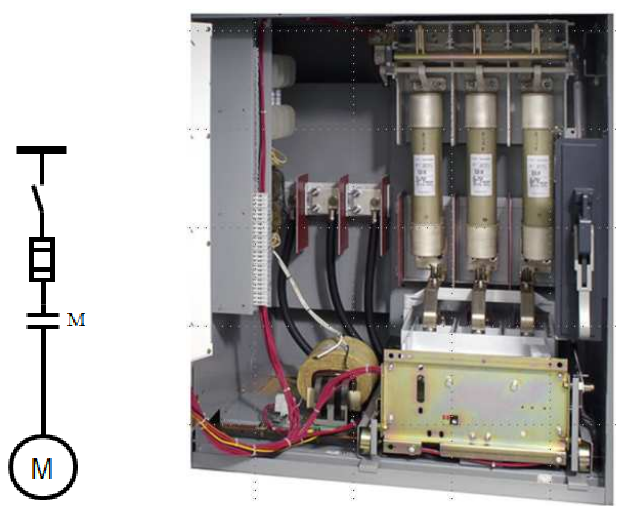

Fig. 3. One-line diagram and photo of a full voltage non-reversing starter

A large inrush or starting current can impact the utility voltage by creating a significant voltage drop across the source conductors and utility impedance. The inrush current drawn by the starting motor is highly reactive, and that reactive power following through the impedance of the system and transformer produces a voltage drop. As the line voltage dips, the electrical toque produced by the starting motor is reduced proportional to the voltage squared, which can lengthen the actual acceleration time.

Fig. 4 shows the voltage at the PCC during the across the line starting of the 4160V, 4157hp motor which stays at or above 0.85pu during motor starting. Start time is less than 11 seconds with acceleration torque above 10% rated and the starting time and current within motor thermal limits.

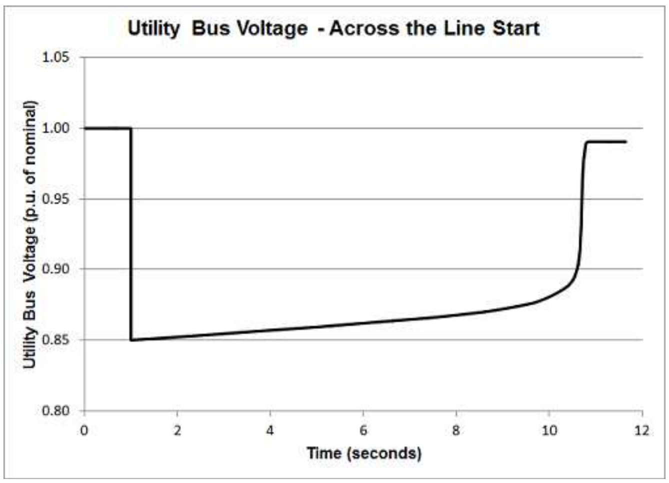


Fig. 4. Utility voltage profile during across-the-line start

*B. Capacitor assisted starting*

During an induction motor start, the inrush current is primarily lagging reactive power. This can be identified by the power factor (PF) at inrush on the motor data sheet, with starting PF of 15 to 25% common. The starting current with lagging PF, i.e. significant reactive power, can be compensated by connecting capacitors to the circuit during the starting period since they provide leading VARs. Capacitors used in motor starting provide local VAR compensation, avoid drawing VARs from the utility through the system impedance, and to help maintain the line voltage. Fig. 5 shows the conceptual one-line capacitor assisted starter consisting of two capacitor steps connected to the motor starter, and a photo of a capacitor bank.

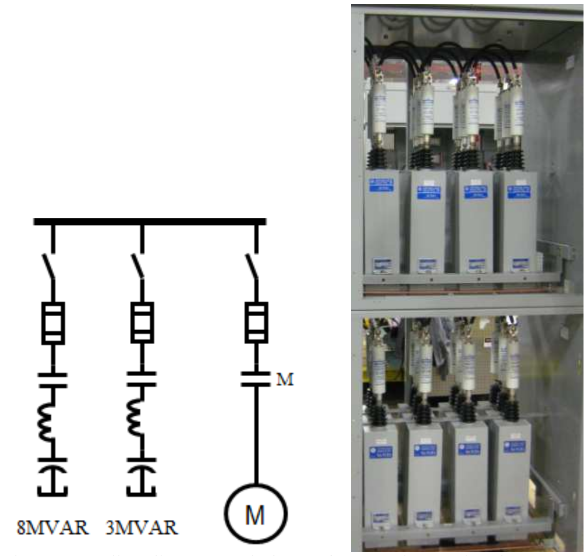


Fig. 5. One-line diagram and photo of a capacitor assisted starter

Difficulties arise with very large induction motors. They require a significant amount of leading VARs during starting. The challenge, this reactive power is only needed during the short starting period, after which it must be removed. The capacitor network is connected prior to the motor start, disconnected before the motor gets to full speed, and optimally disconnected in stages to reduce voltage transients as well as minimize overvoltage as the motor pulls up to speed [1]. This requires complex controls to ensure safe and proper operation/timing of the removal of the capacitor steps.

*1) Initial sizing of capacitor*

For example, this 4175hp compressor draws 6 per unit starting current, and assuming this all reactive power, would require approximately 24MVAR to fully compensate. Since the utility allows 9% voltage drop, partial compensation of 11MVAR was selected. Because the capacitors are only in the circuit for a short time, it is possible to use 2400V, 3.6MVAR capacitors applied at 4160V which gives 3 times the MVAR, i.e. (2.4/4.16)^2 x 3.666 = 11MVAR. For this project 2400V capacitor cans are selected to achieve a higher VAR output while staying within the IEEE 18 temporary over-voltage limits [3].

Based on the full voltage start, the required VAR was shown to be 11MVAR. The capacitor bank selection was split into two sections, 3MVAR and 8MVAR banks. This solution also requires an inrush limiting reactor, capacitor switches (sometimes voltage zero switches), and a control circuit. A multiple timed capacitor stepped starter is not an "off the shelf" solution and requires additional engineering to develop control circuits, capacitor bank arrangements, and capacitor protection schemes. Due to the custom engineering, extra equipment needed for stepped capacitor switching, and large capacitance required, the cost for this solution can be high.

Fig. 6 shows the utility voltage during the capacitor assisted start which stays at or above 0.89pu during motor starting with a total start time of less than 8.5 seconds. Motor acceleration torque was maintained above 10% rated and the starting current within motor thermal limits. Fig. 6 shows the two capacitor steps being removed at the end of the starting period and the motor pulls up to speed. However, this voltage drop exceeded the utility criteria of 9%.

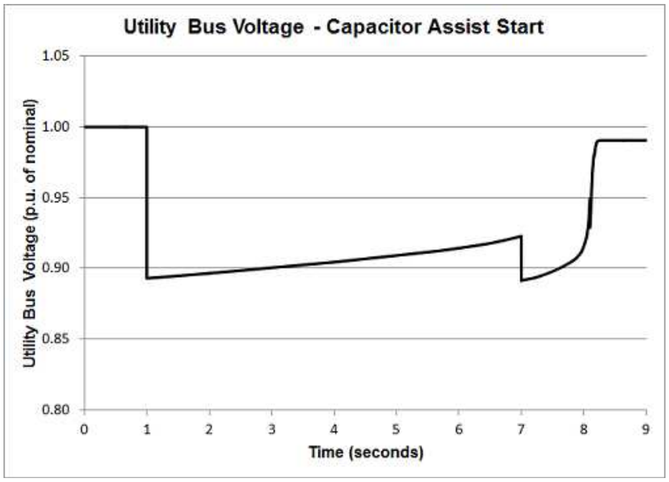


Fig. 6. Utility voltage profile during capacitor assist starting (11MVAR)

*2) Optimal sizing of capacitor*

As an alternative, to start the motor to without exceeding utility voltage drop criteria of 9%, the size of the two capacitor banks were increased to a total of 19MVAR: 12MVAR and 7 MVAR. Fig. 7 shows the voltage drop during starting was well above the allowable voltage drop. However, a voltage transient is visible 7 seconds into the starting sequence. Due to the high transient voltage, complexities in timing of the removal of the capacitor steps, and the cost of the controls and switching, it was not pursued further.

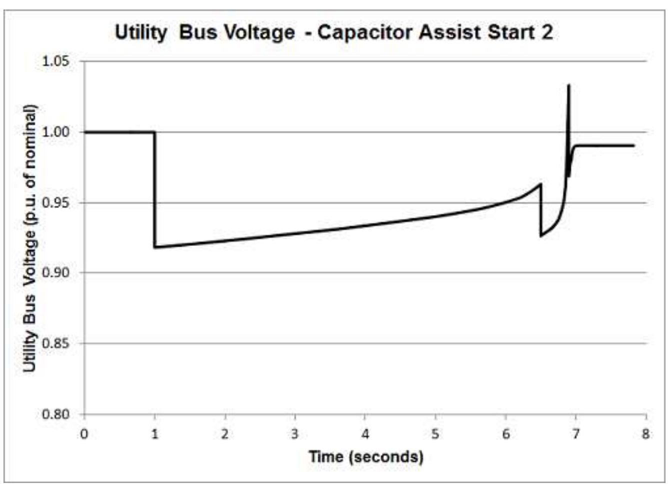


Fig. 7. Utility voltage profile during capacitor assist starting (19MVAR)

*C. Reduced voltage autotransformer*

A reduced voltage autotransformer (RVAT) or Korndörfer motor starter applies a reduced voltage to the motor terminals based on a secondary tap voltage. This secondary tap voltage is typically 50%, 65%, and 80% of nominal line voltage. Motor current is proportional to the motor voltage. Motor torque is proportional to motor horsepower and by reducing both the motor voltage and current, the developed torque is proportional to the product of current and voltage. Percent line current on the line side of the RVAT can be estimated as percent tap multiplied by percent motor current. Moreover, the autotransformer starter provides the most motor torque per line ampere than other conventional reduced voltage starting methods. The cost associated with this type of starter is higher than full voltage starters, but less than most other methods [4].

Fig. 8 illustrates a typical one-line diagram and photo of an RVAT starter. Table 3 provides a reference on the anticipated line to motor performance characteristics. The bottom left shows the main contact, the bottom right shows the RVAT, the top right shows the start contact and run contact, and the top left shows a snubber for transient mitigation. During normal start, the start contactor (S) and then main contactor (M) closes energizing the motor through the RVAT. When the line current drops below a set point, typically 135% of full load amperes, then the start contactor (S) opens and the run contactor (R) closes bypassing the RVAT and connecting the motor to the line for continuous operation.

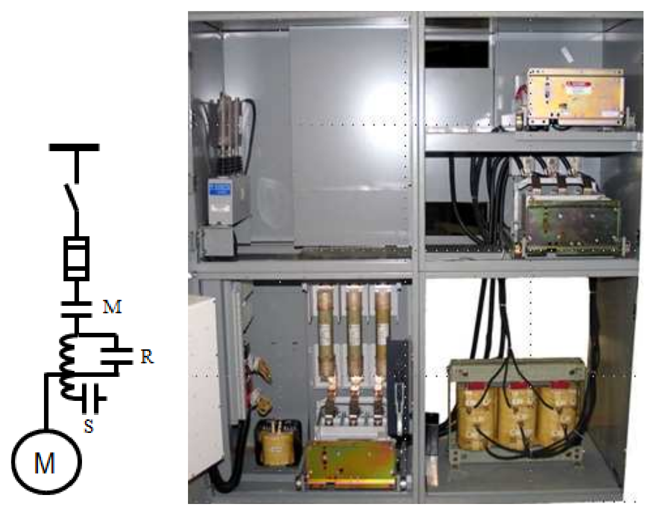


Fig. 8. One-line diagram and photo of a typical autotransformer starter

TABLE III
RVAT - line, motor current and torque relationship

| Line Current | Motor Current | Motor Voltage | Motor Torque |
|---|---|---|---|
| 28% | 50% | 50% | 25% |
| 45% | 65% | 65% | 42% |
| 67% | 80% | 80% | 64% |

The typical 65% and 80% RVAT taps were studied. Fig. 9 shows the utility voltage stays at or above 0.91pu during motor starting at the 65% tap. However, the start time is very long for 65% tap cases, ranging 29 to 34 seconds and the acceleration torque falls below 10% rated for all cases except 80% tap case; motor standards require a minimum of 10% acceleration torque. The starting currents barely fall within motor thermal limits at the 65% tap. Fig. 9 also shows the 80% tap produced higher voltage drops that were further outside the utility requirements. The 50% tap would not start the motor and those simulation results are omitted.

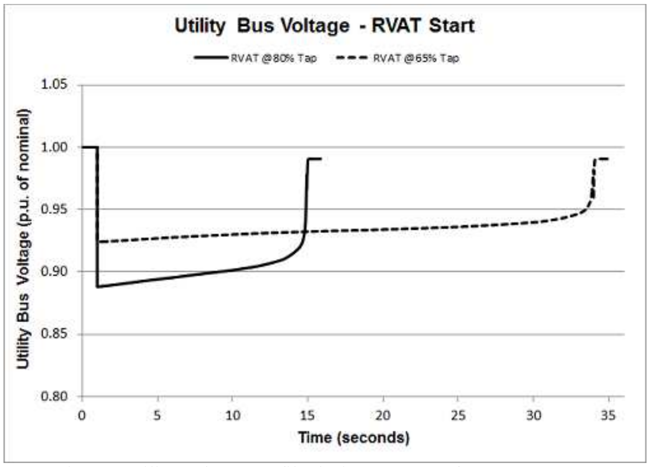

Fig. 9. Utility voltage profile during autotransformer starts

*D. Reduced voltage solid state*

Reduced voltage solid state (RVSS) starter typically use silicon-controlled rectifiers (SCR) to control the voltage applied to the motor. Fig. 10 illustrates a typical RVSS one-line diagram and sample photo. The SCR is gated on at a time between zero volts and peak voltage. The SCR is commutated off by the zero crossing of the AC current waveform. After motor full speed is reached, a bypass contactor (B) is closed, bypassing the SCRs. The feature of solid state starting is programmable current and voltage ramping profiles that control the inrush current to the motor. The current limit range is typically between 200% and 500% of the motor full load amperes [5]. The solid-state starter can reduce the impact to the utility but not as effectively as the autotransformer. However, the solid-state starter can soft-stop or ramp stop the motor. This reduces mechanical stress from an abrupt coast stop. The cost associated with a solid-state starter is higher than an autotransformer starter.

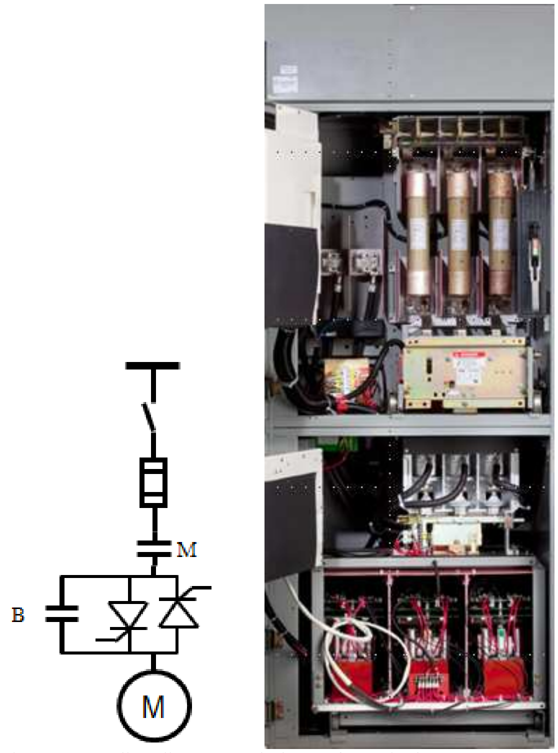

Fig. 10. One-line diagram and photo of a typical RVSS starter

All reduced voltage starting methods reduces the torque the motor can produce. Careful consideration should be made to prevent the motor torque from being reduced below the load torque which can result in a motor stall condition. Also, the overload capacity and firing duration of the SCRs should not be exceeded; this can occur in long acceleration times. Table 4 provides a reference on the anticipated line to motor performance characteristics.

TABLE IV
RVSS - line, motor current and torque relationship

| Line Current | Motor Current | Motor Voltage | Motor Torque |
|---|---|---|---|
| 50% | 50% | 50% | 25% |
| 65% | 65% | 65% | 42% |
| 80% | 80% | 80% | 64% |

Fig. 11 simulation shows the motor current is limited by the RVSS to 1750A or 350% of full load amperes. The analysis showed that the utility voltage stays at or above 0.875pu during motor starting with starting time less than 16 seconds. Acceleration torque is above 10% rated. Starting current are within the motor thermal limits.

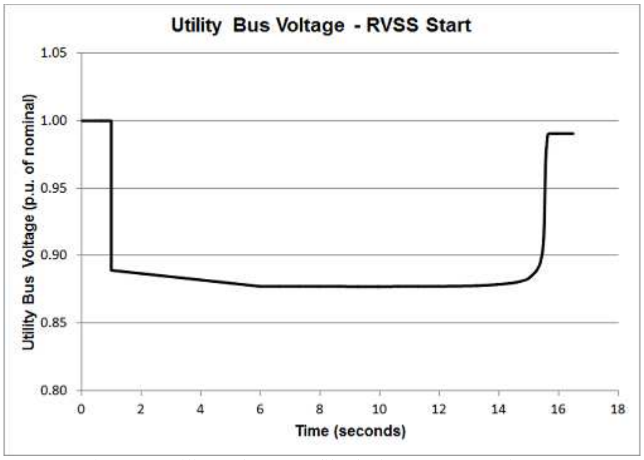


Fig. 11. Utility voltage profile during RVSS starting

### E. *Variable frequency drive*

A variable frequency drive (VFD) converts fixed voltage, fixed frequency input to variable voltage, variable frequency output. This decoupling between the motor and utility provides the optimal starting method. In a voltage source inverter topology drive, the DC bus capacitors provide the motor reactive current. Fig. 12 and 13 illustrate the electrical power schematic of a sample medium voltage variable frequency drive and internal layout image, respectively. Fig. 15 shows a representative one-line diagram. The key components of the MV VFD include primary phase shifting transformer, diode rectifier and insulated-gate bipolar transistor (IGBT) inverter power cells.

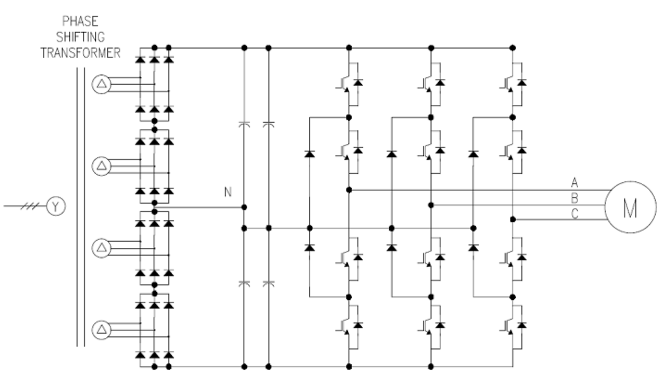


Fig. 12. Layout of a multi-pulse medium voltage diode front end, voltage source inverter (VSI) topology

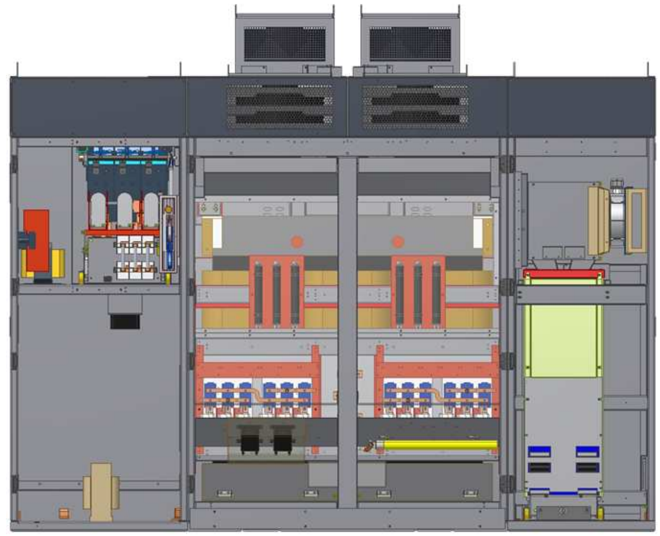

Fig. 13. Internal image of a multi-pulse medium voltage diode front end, voltage source inverter (VSI) topology

The input current to the drive is proportional to the real power required by the motor, load, and any power losses. Typical voltage source inverters (VSI) produce a pulse width modulated (PWM) output waveform to synthesize a variable voltage, variable frequency AC waveform. VFDs can provide a fixed or programmable Volts per Hertz (V/Hz) curve to the motor. The constant V/Hz allows the motor to provide 100% torque throughout the motor rated speed range while keeping motor flux constant [6]. Fig. 14 illustrates the how the motor speed and torque curves change with changing frequency. Unique to this starting method, full rated torque is achievable at stand-still, low speeds up through rated speed which is a significant advantage over the other starting methods analyzed. Although a VFD is ideal for starting the motor, it is the most expensive option. Typical savings are realized from energy savings due to variable speed operation. Table 5 provides a reference on the anticipated line to motor performance characteristics.

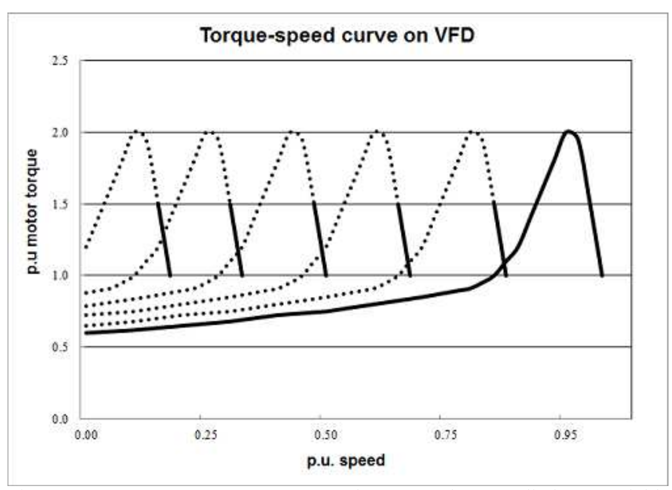


Fig. 14. Motor torque versus speed curve when applied to variable frequency drive output.

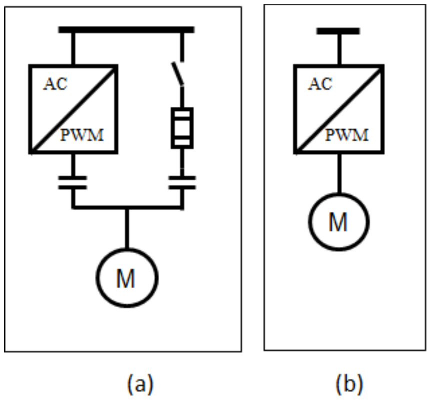


Fig. 15. Variable frequency drive one-line diagram. (a) starting duty rated VFD with synchronous transfer with full voltage bypass motor starter, (b) stand-alone fully-rated VFD

TABLE V
VFD – line, motor current and torque relationship

| Line Current | Motor Current | Motor Voltage | Motor Torque |
|---|---|---|---|
| 10% | 100% | 10% | 100% |
| 50% | 100% | 50% | 100% |
| 100% | 100% | 100% | 100% |

### 1) *Starting Duty Rated VFD*

There is significant cost associated with a fully rated VFD. As an alternative, by utilizing a reduced horsepower or starting duty rated VFD, project costs can be reduced. The VFD is sized to only start the motor and then transfers to a full voltage bypass starter. This is known as synchronous transfer. The VFD output will synchronize with the system voltage and seamlessly transfer the motor from VFD to bypass. It is also possible to transfer the motor back from bypass to the VFD.

Understanding the motor loading during the starting sequence allows a systematic approach to sizing the starting duty rated VFD. Motor data, motor speed/torque curves and load speed/torque curves are used to evaluate the VFD horsepower and load ampere requirements in addition to the estimated acceleration time.

The load torque curve indicates the peak torque required at full speed is approximately 25% of motor rated torque. The motor data sheet indicates at 25% load the required current is 147A, however to provide margin, 50% load and 252A is recommended. For this example, the VFD is sized to 50% of the motor rated horsepower and 51.4% motor rated current. This provides extra accelerating capacity and the option to start the motor under an alternate compressor valve configuration with increased loading.

Fig. 16 show the simulation results for VFD starting where the utility voltage stays at or above 0.98pu during motor starting with starting time less than 8 seconds. Acceleration torque is controlled at 100% rated. Starting current is within the motor thermal limits.

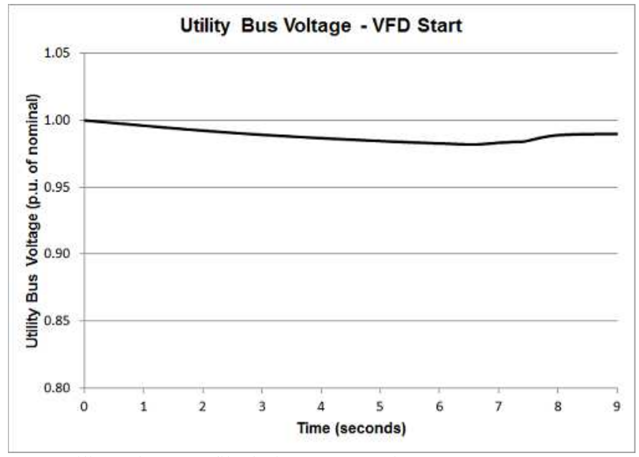


Fig. 16. Utility voltage profile during VFD starting

## IV. Comparison of Performance and PRICE and Selection of the Starting Methods

Each commonly available starter types were evaluated against the project constraint criteria with summary of simulation results shown in Table 6.

- utility voltage drop: 9% from nominal
- acceleration time: 25 seconds or less
- acceleration torque: 10% rated torque or greater

TABLE VI
Comparison of Starting Method Performance

| Starter Type | Voltage Dip | Acceleration | Acceleration Torque | Meets Criteria |
|---|---|---|---|---|
| Full voltage | 15% | 12 sec | > 10% | U |
| Capacitor start | 11% | 8.5 sec | > 10% | U |
| Autotransformer | 8% | 34 sec | < 10% | U |
| RVSS | 13% | 16 sec | > 10% | U |
| Starting rated VFD | 2% | 8 sec | > 10% | A |

A = acceptable
U = unacceptable: 1) exceeds voltage drop of 9%, 2) exceeds acceleration time of 25sec, or 3) less than 10% torque

Each starting method influences the utility line voltage based on the motor inrush characteristics. Although the least costly solution was the full voltage starter, the voltage dip did not meet the utility criteria. Each subsequent starting method improved voltage dip except for the RVSS type. The autotransformer starter did meet the utility requirement but due to the long acceleration time the motor thermal capacity was close to the limit. The RVAT also had the problem of maintaining at least 10% acceleration torque. In addition, the voltage dip level was close to the point at which the grid tie solar inverter shuts off. Ultimately, for these reasons, this method was ruled out. The fully rated VFD was able to meet the utility requirements but an engineered solution was found to reduce the cost while providing the ideal starting condition. The solution chosen was the reduced VFD size with synchronous transfer capability.

When evaluating the requirements for the various types of motor starting methods, economics need to be considered as this can impact the overall project cost. The graph in Fig. 17 takes the base price of a full voltage motor starter and compares to the relative cost of other motor starting method equipment. The motor starting analysis determined a variable frequency drive is required to start the motor to meet the utility requirements. However, due to the compressor characteristics, it can be unloaded during starting. This reduces the VFD size and the overall capital costs can be minimized by selecting a starting duty VFD. Once on bypass, the compressor can be loaded therefore the bypass is sized to handle the full motor load amperes only.

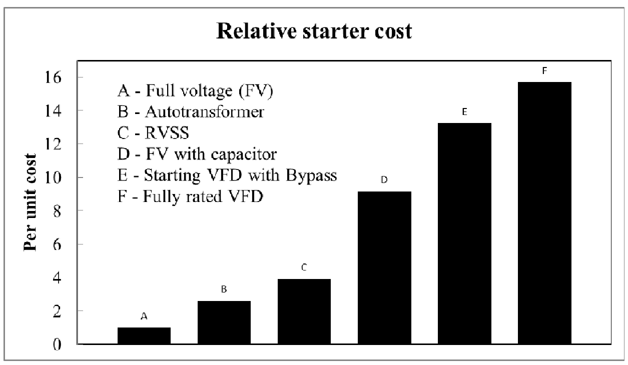


Fig. 17. Relative system cost in per-unit of price compared with a full voltage motor starter

After evaluating all of the price and performance metrics, the best motor starting method for the given project constraints was the starting duty rated VFD with synchronous transfer with full voltage bypass motor starter. The specifications for the starting duty rated VFD are given in Table 7. This drive was subsequently installed at the LNG peak shaving facility and is presently used to start the 4175hp compressor.

TABLE VII
Specifications for the Starting Duty Rated VFD
for 4175hp Compressor Starting

| | |
|---|---|
| Voltage | 4160 V |
| Power | 1865kW (2500hp) |
| Full load amperes | 252 A |
| Overload rating | 110% |
| Frequency | 0 - 60 Hz |

## V. Confirming Performance of the Installed Starting Method

Utility measurements were taken after final installation, start-up and commissioning of the equipment to confirm the simulation results. The utility has a supervisory and data acquisition (SCADA) system that records kW and kVAR demand specifically for this motor starter system. In Fig. 18, the motor is started and transferred to bypass within three minutes. Once on bypass, the compressor load is increased until full capacity is reached. The utility voltage does not dip below 3% for both the starting and running conditions.


Fig. 18. SCADA measurements during VFD: 1) running, 2) off-line, 3) starting, 4) ramp-up to running conditions.

Fig. 19 is an oscilloscope waveform capture during the commissioning of the VFD when the utility and VFD output voltage synchronization is verified. The magenta lines are utility voltage measurements at 500 milliseconds per division. The arrow is the region when the motor is transferred to bypass operation. There is a slight drop in voltage magnitude, however it is when the motor is in bypass and not when controlled by the VFD.

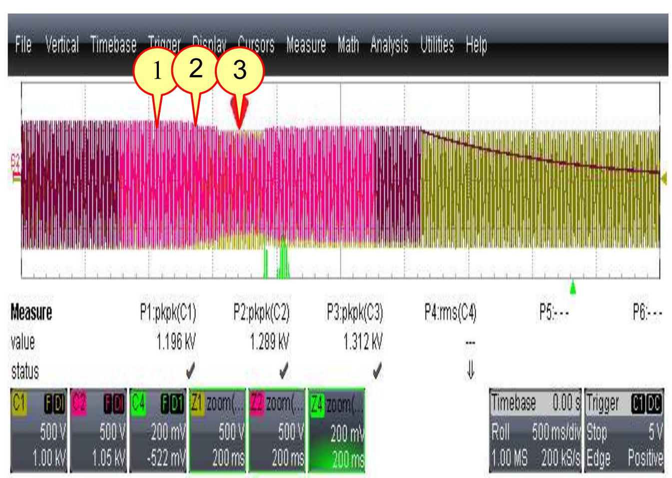


Fig. 19. Line utility voltage measurements during VFD: 1) offline, 2) starting, and 3) bypass closed conditions.

## VI. Conclusion

This paper illustrated that understanding the impact to utility voltage while starting large horsepower induction machines is critical to the reliability and continued operation of any industrial facility. The extensive simulation modeling showed common motor starting methods available and the resulting impact to the utility. The modeling and cost analysis provided a means to determine the best solution given the project constraints, i.e. starting duty rated VFD with synchronous transfer with full voltage bypass motor starter. The method employed to start the compressor load fulfilled the project and utility requirements as confirmed by performance measurements at the time of commissioning and ongoing measurements through the utility SCADA system. The approach to analyzing new and conventional starting methods is applicable to large motors applied on a variety of systems.

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